Lifecycle Assessments (LCAs)

Lifecycle assessment, together with lifecycle thinking and lifecycle management, are systems approaches for addressing the environmental consequences of an entire product chain, from resource extraction to waste management. Lifecycle assessments are used in business and policy making to promote sustainable consumption and production. They offer alternatives to point-source strategies, which only reduce pollution at its source.

Lifecycle assessment (LCA) is a method of analyzing the environmental impacts associated with a product or service. The method studies the material and energy flows throughout the product or service system, from raw materials extraction, through production and use, to disposal.

An LCA study is defined both by the product system it covers and the procedure used to study it. The procedure consists of several steps. Researchers start by developing the goal and scope definition, which specifies the product to be studied and the purpose of the LCA study. In the inventory analysis step, they construct the lifecycle model of the product system and calculate the amounts of emissions produced and the resources used in the product system, such as raw materials and energy. During the impact assessment step, the researchers relate emissions and resource use to potential environmental problems (e.g., resource depletion and global warming) by classifying and characterizing the environmental impacts. In the weighting step, they add up the different environmental impacts by applying factors that indicate their relative significance, and then they calculate the total environmental impact of the studied product system. The interpretation step is an iterative process of evaluating the modeling of the product system. During this step, the researchers adjust the methodological choices to suit the purpose and the stakeholders of the study and to evaluate the quality of the results.

Some formalized definitions of LCA are found in publications such as the Society of Environmental Toxicology and Chemistry (SETAC) guidelines (Consoli et al. 1993) and the International Organization for Standardization standards on LCA (ISO 2006). A comprehensive description of the development, methodology, and the application of LCA appears in the textbook by professors Henrikke Baumann and Anne-Marie Tillman (2004) and in the operative guidelines to the ISO standard on LCA (Guinée 2002).

When the results are presented as the amount of emissions and resources used per functional unit, they are called an LCI, or lifecycle inventory, study. Usually LCIs identify a large number of pollutants and resources, sometimes more than two hundred parameters, making it difficult to summarize the results. Results can also be presented at different levels of aggregation: as inventory results that identify the gases and chemicals emitted during production; as characterization results that identify environmental impacts such as acidification, eutrophication, and global warming; or as results weighted together into a one-dimensional indicator, or one number that indicates the total environmental impact according to various methods. By grouping inventory results into impact categories, researchers can calculate the characterization results, leading to fewer parameters (Guineé 2002). It is possible to further aggregate results through various formalized weighting methods. Different weighting methods express different ways of prioritizing environmental problems. For example, priorities can set through political policies with environmental goals, recommendations by Delphi panels (experts who work together to forecast and revise results), or economic policies that encourage a "willingness to pay" to avoid environmental problems.

Methodologies

LCA is principally a methodology for comparing equivalent product systems, although a stand-alone LCA comparison is also possible. In a stand-alone LCA, researchers compare different parts of one product system. In all types of LCAs, they make a comparison by relating environmental impact to a unit that expresses the function of the product system. For example, beverage-packaging systems can be compared on the environmental impact per liter of packaged drink. The unit of comparison is called the functional unit, and its definition is essential for conducting a fair comparison. Other methodologies that influence the quality of a comparison include the system boundary definition (e.g., deciding whether to include in the system items such as the production of capital equipment), the types of environmental impacts being considered (e.g., aiming at a comprehensive evaluation of environmental impacts versus limiting the study to one or two impact categories), and the level of detail in the study (e.g., deciding whether to use site-specific data or average data over a number of production sites).

Different types of LCA are possible, depending on how the comparison is made. In quantitative LCA studies, researchers calculate the environmental impacts for the product systems, whereas in qualitative LCAs, they identify and evaluate the environmental impacts through reasoning supported by, for example, checklists. Another distinction concerns whether the comparison is prospective or retrospective. In a prospective study, researchers investigate the environmental consequences of the proposed changes to an existing product system. An example is a study of the significance of possible waste-management alternatives (e.g., recycling and incineration) to an existing packaging system. Prospective studies are also called change-oriented LCAs or consequential LCAs. In a retrospective LCA, often called an accounting LCA, researchers compare existing product systems. The comparison of ecolabeled products typically builds on an accounting LCA. (Ecolabeling is a voluntary program in which manufacturers and service providers certify the environmental performance of their products and services.)

The distinction between the change-oriented / consequential LCA and the accounting/retrospective LCA is a difference in focus: in one, the existing situation is compared to an alternative future situation (change-oriented / consequential LCA), and in the other, two existing alternatives are compared (perspective/accounting LCA). In addition, system boundary definition and data choices differ substantively between these two types of LCA study. Studying the consequences of change typically leads to a focus on modeling the parts of the system that are affected by change and to the use of marginal data. But comparing the existing products typically leads to a focus on how complete the model of the product systems is and to the use of average data.

Cradle to grave, *cradle to gate*, and *gate to gate* are other terms for LCA. They indicate the extent to which the product system is modeled in an LCA, from raw materials extraction to waste management, to the factory gate, or between factory gates, respectively.

LCA is also associated with the philosophy of lifecycle thinking (LCT) and the practices of lifecycle management (LCM). Expressions of lifecycle thinking can be found in, for example, corporate environmental policies. Lifecycle management is the managerial practices and organizational arrangements that result from lifecycle thinking. LCM's goal is to coordinate environmental concerns and work among actors within the product system, rather than develop independent measures in each company (cf. Remmen, Jensen, and Frydendal 2007).

History

The development of early LCA between 1969 and 1989 is distinct from its development afterward. Since 1990, systematic description and the development of the methodology has come to the fore, making it a subject of academic study. It was not until the early 1990s that the term *lifecycle assessment* came into general use—earlier studies were called ecobalances, resource and environmental profile analyses, or cradle-to-grave studies.

A study conducted in the United States for Coca-Cola by the Midwest Research Institute from 1969 to 1970 is generally considered the first LCA study. Early independent studies were also conducted both in the United Kingdom (for Schweppes by Ian Boustead) and in Sweden (for Tetra Pak by Gustav Sundström). All the early LCAs between 1969 and 1972 studied packaging and waste management. They coincided with the environmental debate concerning wasteful resource use and disposable packaging in throwaway societies (Meadows et al. 1972). What identifies these studies as LCAs is their simultaneous attention to material and energy flows, from raw materials extraction to the waste disposal of a product system and the pollution and resource use associated with it. This distinguishes them from the systems studies focusing on energy that became common after the oil crisis in 1973. Nevertheless, the oil crisis fueled interest in LCA, and a handful of consultants in the world carried out small-scale LCA studies.

Between 1970 and 1989, the consultants William Franklin and Robert Hunt conducted some two hundred studies in the United States, and consultant Gustav Sundström conducted about one hundred studies in Sweden, many of them for private companies. LCA resurfaced in the public debate with the surge of environmental interest during the mid-1980s, again in relation to packaging. In 1984, the Swiss environmental agency conducted a large packaging study (Bundesamt für Umweltschutz 1984) that was widely criticized. The study was updated five years later (Bundesamt für Umwelt, Wald und Landschaft 1989). Its criticism paradoxically increased attention toward the possibilities of LCA and inspired packaging studies in other European countries (e.g., in Denmark in 1990, in Sweden in 1991, and in the Netherlands in 1992). The many packaging studies showed diverging results and partly differing methodologies, starting a new era of methodological discussion and development.

The increased interest in LCA can be explained by industry's shift in focus toward environmental work. Since the early 1990s, manufacturers have increasingly supported the idea that environmental protection should go beyond "end-of-pipes" strategies that deal with pollution after it happens. Many of those in industry see the environmental optimization (identifying where reductions like waste minimization and material substitution can be most efficient) of products as an effective path toward sustainability. LCA's appeal is that it deals with environmental issues in a systematic and comprehensive way, handling several environmental problems at a time and extending the environmental analysis beyond controlling emissions at their point source. In doing so, LCA helps avoid suboptimization, or settling for a lesser outcome, in the environmental management of industrial systems.

Guidelines, Standards, and Developments

The Society of Environmental Toxicology and Chemistry (SETAC) provides a forum for discussing LCA experiences and developing an international consensus on a "harmonized LCA methodology" (Consoli et al. 1993). After sponsoring seven international workshops and conferences between 1990 and 1993, it published the first international guidelines in its code of practice (Consoli et al. 1993). It also established a number of working groups to speed up the process of developing a standardized methodology. The first international standard for LCA, providing its main principles and framework, was issued in 1997 by the International Organization for Standardization. Since then a series of LCA standards have been issued and updated. Other organized efforts to promote LCA take place, for example, through the Life Cycle Initiative, a collaboration between the United Nations Environment Programme (UNEP) and SETAC. This initiative's goals include disseminating widely accepted methods for the reliable and easy use of LCAs, first to developing countries and later more widely (Life Cycle Initiative n.d.). The European Commission also supports the dissemination of LCA through policy and business practices (European Commission—Joint Research Centre 2009).

The core of LCA—flow modeling—has remained much the same since the beginning, while impact assessment methodologies saw the most advances during the 1990s. Since 2000, methods have been developed that include the social aspects in lifecycle impact assessment and the economic cost-benefit analysis along the product chain. These developments better align LCA with the discourse of sustainable development and make LCA more attractive to the business community. But much work remains before such methods become common practice. Much work also went into the development of software, databases, and standardized formats for data exchange: simple data management is crucial to facilitating calculation and data availability since any LCA study requires much data. The exploration of alternative data sources, such as economic input-output tables, led to new types of LCA: IO-LCA (input-output LCA) (Hendrickson, Lave, and Matthews 2006) and hybrid LCA, which combines standard LCA with IO-LCA (Suh et al. 2004). These methods enable researchers to conduct new types of studies (cf. Tukker and Jansen 2006) that explore the consumption activities that have the most-polluting product flows in society (typically transportation, housing, and food). Since these studies include the impacts of production that is outsourced to developing countries, they contribute to the debate on the role of consumption and global industry in sustainability (cf. Hertwich 2005).

A scholarly journal for developments in the field of LCA, *The International Journal of Life Cycle Assessment*, began publishing in 1996. The first conference on lifecycle management was held in 2001, and the European network on IO-LCA also held it first meeting in 2001. In short, research related to LCA, LCT, and LCM is mainly prescriptive, dealing with methodology development. Consequently research exploring the practices of LCA and LCM is less common.

Applications

LCA and LCT attract interest both in business and policy making. Policy makers use LCA in studies to guide policy development away from point-source control and into product-oriented policy making. For example, the packaging studies that were discussed above in the history section were often used to identify which materials should have recycling policies. LCT gave rise to the notion of extended producer responsibility, in which a consortium of companies is responsible for the environmental costs of their products through the end of the products' lifecycles. The result is producer take-back policies that require the manufacturer to pay for the collection, disposal, and recycling of their products. Other lifecycle-influenced policies include ecolabeling, which was discussed along with methodology. The application of LCT to policy making is, however, a challenge: the global nature of business spreads material and energy flows outside the reach of governmental policy makers.

Since the 1990s, LCA has been applied to nearly all sectors of business and society. In the transportation sector, LCA studies are often called well-to-wheel studies. LCA's focus on products has made it particularly applicable to product development and ecodesign as well as ecolabeling. The prescriptive use of LCT in the sustainable design of products and services, for example, appears in cradle-to-cradle design model (McDonough and Braungart 2002). LCA-based ecolabeling schemes have been put forward both by governmental organizations (as in the European Union's "Flower" ecolabel) and by industrial coalitions (as in the International EPD Consortium's Environmental Product Declaration scheme). LCA has also been applied to "greening" the control methods of manufacturing and production systems. Upstream application areas, which occur in the manufacturing and production stages, include greening supply-chain management and procurement. Downstream application areas, which occur around the sale of the product, include waste and recycling management. Several LCA tools are specially adapted to the requirements of the various fields of application.

Despite its widespread use and application, LCA's use in business is relatively limited. Surveys on businesses' adoption of LCA are rare. In 2002, almost 10 percent of the largest corporations in Europe worked with LCA in some way. Compare this with the percentage of corporations that adopted environmental management systems: almost two-thirds in the same survey (Hibbitt and Kamp-Roelands 2002). One reason for this difference is that LCA reaches outside a company's normal boundaries of responsibility. This makes LCA irrelevant or overambitious in the eyes of some; alternatively, others believe it offers a novel and useful perspective on business operations. Most LCA studies done for companies are conducted by consultants or through collaborations with research institutes, sector organizations, or academia. In companies where the LCA process has been internalized, it is typically an experimental activity performed by the environmental or research and development department (cf. Frankl and Rubik 2000; Rex and Baumann 2007). Analysis shows that LCA studies often lead to organizational learning, a new and widened perspective on business operations, and, often, surprising insights. In just one such example, people in a paper mill were about to reduce their point-source emissions by investing in more state-of-the-art, end-of-pipe technology, but they realized through an LCA that they could save money and reduce their emissions tenfold through simple changes in the logistics from forest to mill (Baumann and Tillman 2004).

Little is known about the business rationales for LCA since proponents inside the company drive much of the LCA work. But studies show that, in companies where LCA practices are institutionalized, risk aversion or trust-building with actors in the supply chain are the business rationales for LCA (Rex and Baumann 2007). In these companies, specially adapted LCA tools and considerations were implemented in the business process, for example, in product development or procurement. The same studies also show that LCA practices differ greatly among businesses, even between similar, same-sector companies. For example, LCA practices in product development in European truck companies range from using simple LCA-based guidelines to combining extensive LCA studies with strategic planning.

Implications

There are many controversies over LCA methodology. Concerns about the inappropriate use of LCAs in the United States led a coalition of state attorneys general to decide that "the results of LCAs should not be used to advertise or promote specific products until uniform methods . . . are developed" (ENDS 1991). Such concerns are strong reasons for standardization efforts. Because LCA is quantitative and describes physical flows with scientific methods, it is often thought of as an objective method that produces general scientific results. But this is far from the case. Many methodological choices depend on the purpose and the type of LCA. Methodological alternatives are also a matter of choice. Eventually gaps and unresolved ambiguities develop in the methodology. Together, these issues lead to the possibility that similar LCA studies would have divergent results. Such results pose special problems for the ISO standard on LCA, since it aims to be a comprehensive standard for all types of LCA.

Debate is particularly intense and enduring over two issues: how to allocate environmental loads across several products, and how to conduct impact assessment. Since LCA focuses on a single product at a time, the material flows of different products being connected to each other can complicate the inventory analysis. Whenever more than one product is produced in a process, an allocation problem occurs in the LCA. It also arises when many products are collectively treated in the same waste-treatment process and when a product's material is recycled into another product. The allocation problem concerns how the environmental loads of a process are divided among the process's different products. Several methods exist for dealing with this, including applying various principles to partition the environmental loads onto the products based on physical relationship, weight, volume, or economic value. Another approach is system expansion, which includes the parts of the surrounding industrial system that are affected by changes related to the object of study. Some people argue for strict recommendations for partitioning the environmental loads, and some argue for more-open recommendations that allow researchers to choose the method depending on the purpose of the study. The ISO standard is contradictory because it acknowledges both the need to choose the method based on the goal and prescribes an allocation procedure that ignores the goal-dependant method.

Many debates about impact assessment concern what counts as an environmental impact and where to model the impact in the cause-effect chain between emissions and their effects. Methodology is being developed to cover additional types of impacts, including some social and economic impacts. Some impacts are difficult to describe; for example, the effects of ecotoxicity and land use on biodiversity result in LCA studies that emphasize easily modeled impacts. Some researchers debate whether to describe impacts through end-point or midpoint assessment, that is, whether the methodology should describe real or potential impacts. The significance is that real impacts depend on the location of the impact, which adds geographical complexities to modeling. As a result, several impact assessment methods exist. Many of these methods conflict with work on potential impacts, thereby rendering them generally applicable but inaccurate.

The time and resources it takes to carry out an LCA study have always been a contentious issue, and many claim that the costs of performing the lifecycle inventory are too high. Efforts to simplify the execution of LCA studies take various paths. One path develops screening and streamlining methodologies that drastically reduce the amount of data needed. An alternative path increases the availability of data by setting up and maintaining databases for researchers to use.

Research activities also reflect different perspectives on how to further the use of LCA. The dominant approach intended to resolve the methodological problems in LCA, and it led to many prescriptive, relatively realistic recommendations concerning LCA's application. A small but growing body of knowledge aims to develop an understanding of practices related to LCA, LCT, and LCM in business and policy making. This more descriptive research indicates that many of the prescriptive recommendations for LCA application are too general to fit a diverse business community.

Many find LCA complicated and time consuming, but this is more a case of LCA reflecting the complexities of our world. LCA offers a systematic way to describe the environmental consequences of production and consumption in a comprehensive way that enables communication about large, complex environmental issues. LCA development has mostly taken place in the engineering community, but cross-disciplinary integration with the social, economic, and management sciences is increasing. Such integration can modify the technical LCA approach to be more useful for business and other actors in society.

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See also Biomimicry; Cradle to Cradle; Design, Industrial; Ecolabeling; Energy Efficiency; Integrated Product Development (IPD); Manufacturing Practices; Natural Step Framework, The (TNSF); Product-Service Systems (PSSs); Remanufacturing; Zero Waste

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